GLOSSARY OF ACRONYMS AND ABBREVIATIONS

APD	Amplitude Probability Distribution
ARNS	Aeronautical Radionavigation Service
BL	Break-Lock
C/A	Coarse/Acquisition
C/N_0	Carrier-to-noise Power Density Ratio
CDMA	Code Division Multiple Access
CFR	Code of Federal Regulations
CMC	Code Minus Carrier
CW	Continuous Wave
dB	Decibels
dBi	Decibels relative to an isotropic antenna
dBic	Decibels relative to an isotropic circularly polarized antenna
dBm	Decibels relative to one milliwatt (equal to -30 dBW)
dBW	Decibels relative to one watt (equal to 30 dBm)
DGPS	Differential Global Positioning System
DNBL	Did Not Break lock
E-911	Enhanced-911
EIRP	Equivalent Isotropically Radiated Power
EMC	Electromagnetic Compatibility
ER	En-Route Navigation
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FTE	Flight Technical Error
GEO	Geostationary Earth Orbiting
GHz	Gigahertz
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
IF	Intermediate Frequency
IGEB	Interagency GPS Executive Board
IRAC	Interdepartment Radio Advisory Committee
ITS	Institute for Telecommunication Sciences
ITU-R	International Telecommunication Union - Radiocommunication Sector
kHz	kilohertz
L1	GPS Link 1 (1575.42 MHz)
L2	GPS Link 2 (1227.60 MHz)
L5	GPS Link 5 (1176.45 MHz)
LAAS	Local Area Augmentation System
LNA	Low Noise Amplifier
LOS	Line-of-Sight
LR	Loss Ratio
MDH	Minimum Descent Height

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

MHz	Megahertz
ms	millisecond
MSS	Mobile Satellite Service
NASA	National Aeronautics and Space Administration
NOI	Notice Of Inquiry
NPA	Non-Precision Approach
NPRM	Notice of Proposed Rulemaking
NSE	Navigation System Error
NTIA	National Telecommunications and Information Administration
OOK	On-Off Keying
OSM	Office of Spectrum Management
PDOP	Position Dilution Of Precision
PRF	Pulse Repetition Frequency
PTC	Positive Train Control
RMS	Root-Mean-Square
RNSS	Radionavigation Satellite Service
RTCA	RTCA, Inc.
RQT	Reacquisition Time
TSE	Total System Error
TSO	Technical Standard Order
USCG	United States Coast Guard
UWB	Ultrawideband
WAAS	Wide Area Augmentation System

SECTION 1.0
INTRODUCTION

1.1 BACKGROUND

The National Telecommunications and Information Administration (NTIA) is the Executive Branch agency principally responsible for developing and articulating domestic and international telecommunications policy. NTIA's responsibilities include establishing policies concerning spectrum assignments, allocation in use, and providing various departments and agencies with guidance to ensure that their conduct of telecommunication activities is consistent with these policies.[7] Accordingly, NTIA conducts technical studies and makes recommendations regarding telecommunication policies and presents Executive Branch views on telecommunications matters to the Congress, the Federal Communications Commission (FCC), and the public.

NTIA is responsible for managing the Federal Government's use of the radio frequency spectrum. The FCC is responsible for managing the spectrum used by the private sector, and state and local governments. In support of its responsibilities, the NTIA has undertaken numerous spectrum-related studies to assess spectrum utilization, examined the feasibility of reallocating spectrum used by the Federal Government or relocating Federal Government systems, identified existing or potential electromagnetic compatibility (EMC) problems between systems, provided recommendations for resolving any EMC conflicts, and recommended changes to promote efficient and effective use of the radio frequency spectrum and to improve Federal spectrum management procedures.

In February,1998, U.S. Radar Inc., Time Domain Corporation, and Zircon Corporation, each petitioned the Commission for a waiver [8] of the Code of Federal Regulations, Title 47, Part 15 of the FCC rules.[9] The Part 15 rules authorize the operation of certain radio frequency devices without an individual station license from the FCC or the need for frequency coordination.[10] Within the Part 15 Rules, intentional radiators are defined as transmitters that are permitted to

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[7] NTIA, "Manual of Regulations and Procedures for Federal Radio Frequency Management", U.S. Department of Commerce, National Telecommunications and Information Administration (January 2000 Edition with revisions).

[8] *U.S. Radar Inc. Request for a Waiver of Part 15 for Ground Penetrating Radar* (Jan. 28, 1998), DA 98-221; *Time Domain Corporation Request for Limited Waiver of Part 15 of the Commission's Rules to Permit Authorization of Ultra-Wideband Time Modulating Technology* (Feb. 2, 1998), DA 98-222; and *Zircon Corporation Request for a Waiver of Part 15 for an Ultra-Wideband System* (April 14, 1998), DA 98-924.

[9] Title 47 Code of Federal Regulations § 15.1 (hereinafter "47 C.F.R.").

[10] 47 C.F.R. § 15.5. The primary operating conditions under Part 15 are that the operator must accept whatever interference is received and must correct whatever interference is caused. Should harmful interference occur, the operator is required to immediately correct the interference problem, even if correction of the problem requires ceasing operation of the Part 15 system causing the interference.

operate under a set of general emission limits,[11] or in some cases under provisions that allow higher emission levels in certain frequency bands.[12] Intentional radiators generally are not permitted to operate in certain sensitive or safety-related frequency bands, designated as the restricted bands.[13] Because the waiver requests included Part 15 restricted frequency bands that are allocated for use by the U.S. Government, these requests were closely coordinated with NTIA. After discussions within the Interdepartment Radio Advisory Committee (IRAC), NTIA informed the FCC that the waivers could be granted with conditions that, among other things, required that: 1) all UWB operations be fully coordinated with the Frequency Assignment Subcommittee of the IRAC; 2) there will be limited distribution of the UWB equipment; and 3) records will be maintained for all users to whom the manufacturers sell, lease or otherwise distribute UWB equipment.[14] As a result of the conditions specified by NTIA, the three waiver requests were granted on June 25, 1999 by the Chief of the FCC's Office of Engineering and Technology.

In September 1998, the FCC issued a Notice of Inquiry (NOI) to investigate the authorization of Ultrawideband (UWB) transmission systems on an unlicensed basis under the Part 15 rules.[15] The responses to the NOI affirmed that recent advances in microcircuits and other technologies have resulted in the development of pulsed radar and communication systems with very narrow pulse widths in the time domain and very wide bandwidths in the frequency domain. These UWB transmission systems may be able to perform a number of useful radiocommunication functions that could make them very appealing for both commercial and government applications. UWB transmission systems can have very wide information bandwidths, are capable of accurately locating nearby objects, and can utilize signal processing technology with the UWB pulses to enable the devices to "see through objects" and to communicate in severe multipath environments.

The responses to the NOI also highlighted two primary obstacles that the current Part 15 Rules pose on the implementation of UWB transmission systems. First, the wide bandwidth that is intrinsic to the operation of UWB transmission systems can result in the transmission of the fundamental emission in restricted frequency bands, which is prohibited under the existing Part 15 Rules. Second, the current emission measurement procedures specified in the Part 15 Rules were developed for narrowband systems and therefore, may be inappropriate for, and may even pose unnecessary restrictions on UWB transmission systems, particularly impulse systems.

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[11] 47 C.F.R. §15.209.

[12] 47 C.F.R. §§ 15.215-15.407. In some cases, operation at the higher emission levels within these designated frequency bands is limited to specific applications.

[13] 47 C.F.R. §15.205.

[14] Letter to Mr. Dale Hatfield, Chief, Office of Engineering and Technology, Federal Communications Commission from William T. Hatch, Acting Associate Administrator, National Telecommunications and Information Administration, Office of Spectrum Management (Jun. 15, 1999).

[15] *Revisions of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems*, Notice of Inquiry, ET Docket No. 98-153, 63 Fed. Reg 50184 (Sept. 21, 1998).

The FCC initiated a process to develop policy and regulatory decisions by releasing a Notice of Proposed Rulemaking (NPRM)[16] proposing regulations authorizing the operation of some UWB transmission systems on an unlicensed basis under the Part 15 Rules. The UWB NPRM contains a series of proposals and questions that can be grouped into the following broad categories: regulatory treatment, UWB definition, frequency bands of operation, further testing and analysis, emission limits, measurement procedures, prohibition against Class B damped wave emissions, and other matters. The FCC has specifically proposed that safety services, such as the Global Positioning System (GPS), be protected from harmful interference.[17]

GPS is an example of a critical radionavigation system that uses operating frequencies in the restricted frequency bands. GPS has become the preferred navigation system for aviation (en-route, precision and non-precision approach) and maritime operations. In order to meet the exacting standards required from a safety-of-life system, the U.S. Government has either developed or is developing augmentations to GPS for aviation, maritime, and land use. The Wide Area Augmentation System (WAAS) and the Local Area Augmentation System (LAAS) are under development to enhance aviation uses of GPS.[18] Differential GPS (DGPS) has been fielded to augment GPS for maritime use in intercoastal and inland waterways. GPS is also fast becoming an integral component of position determination applications such as Enhanced-911 (E-911) and personal location and medical tracking devices. The telecommunications, banking, and power distribution industries represent another sector that uses GPS for network synchronization timing. Moreover, GPS has proven to be a powerful enabling technology that has driven the creation of many new industries. GPS also provides the U.S. military and its allies with positioning, navigation, and timing capabilities that are critical to peacetime and wartime national and global security operations. Although these examples are not all inclusive, they illustrate the widespread use, and in many cases, dependence on the uninhibited availability of the GPS signals.[19]

Thus, NTIA accepted funding from the Interagency GPS Executive Board (IGEB) and the Federal Aviation Administration (FAA) to perform an assessment of the EMC between proposed UWB devices and GPS receivers.[20] The measurement component of this assessment was conducted by NTIA's Institute for Telecommunication Sciences (ITS) and the analyses portion

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[16] *Revisions of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems*, Notice of Proposed Rulemaking, ET Docket No. 98-153, FCC 00-163 (rel. May 11, 2000) (hereinafter "UWB NPRM").

[17] *Id.* at ¶ 23, 28, and 29.

[18] U.S. Department of Transportation and U.S. Department of Defense 1999 Federal Radionavigation Plan (Dec. 1999) at 1-11 (hereinafter "1999 FRP").

[19] GPS currently emits a civil signal centered at 1575.42 MHz (L1); however, an ongoing modernization effort will include new civil signals centered at 1227.60 MHz (L2) and 1176.45 MHz (L5).

[20] The UWB emissions considered in this assessment are limited to those using a burst of a series of impulse-like signals. However, there are several ways of defining UWB signals, one being emissions that have an instantaneous bandwidth of at least 25% of the center frequency of the device. There are also several ways of generating very wide signals, including the use of spread spectrum and frequency hopping techniques.

was performed by the NTIA Office of Spectrum Management (OSM). This document provides a description of the methods used and the results obtained from these measurements and analyses. A separate report, prepared by ITS, that presents the measured data in post-processed format and provides details of the measurement procedures and equipment used to acquire the data, is available and is referenced throughout this report.[21]

1.2 OBJECTIVE

The objective of this assessment was to define the maximum allowable UWB equivalent isotropically radiated power (EIRP)[22] levels that can be tolerated by GPS receivers used within various operational applications without causing degradation to their operations. These EIRP levels will then be compared to the existing Part 15 emission limits[23] to assess the applicability of these limits to UWB devices.

1.3 APPROACH

A two-part approach consisting of both a measurement and an analysis component was adopted for this assessment. First, a measurement effort was undertaken to determine the interference threshold for different GPS receiver architectures to a set of UWB waveforms. Utilizing the measured GPS receiver interference threshold, analyses were performed for various operational scenarios to determine the maximum allowable UWB EIRP level, in the GPS frequency band, that can be tolerated by a GPS receiver before a performance degradation is realized.

1.3.1 Measurement Approach

The first activity associated with this project was the development of a plan to guide the measurement of GPS receiver susceptibility to UWB signals. In the formulation of a measurement plan, NTIA considered a number of factors including which GPS receivers to measure, what UWB signal parameters to examine, and what GPS receiver performance metrics and criteria to apply. Also as a part of the formulation of the measurement plan, a set of measurement procedures were developed with the intent that if followed, these procedures would lead to repeatable measurement results.

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[21] NTIA Report 01-384 "Measurements to Determine Potential Interference to GPS Receivers from Ultrawideband Transmission Systems", U.S. Department of Commerce, National Telecommunications and Information Administration, Institute for Telecommunication Sciences, (hereinafter "ITS Report").

[22] The computation of EIRP is in terms of the average power of the UWB signal for all cases considered in this report. This average power is based on root-mean-square (RMS) voltage.

[23] The existing Part 15 measurement procedure uses an average logarithm detector process and is not equivalent to measurements using an RMS detector process. See NTIA Special Publication 01-43, "Assessment of Compatibility Between Ultrawideband Devices and Selected Federal Systems," at 2-1 for discussion of the differences in measuring average power vs. log average power.

After the measurement plan was completed and made available to other Government agencies for review and comment, NTIA sought public comment in a notice published in the Federal Register.[24] The following seven parties submitted comments to the NTIA announcement;

- Air Transport Association
- ANRO Engineering, Inc.
- Multispectral Solutions, Inc.
- National Aeronautics and Space Administration (NASA) Glenn Research Center
- RAND Science and Technology Policy Institute
- Time Domain Corporation
- United States GPS Industry Council.

NTIA considered the comments, made appropriate changes to the measurement plan, and provided a response for each commenter for the public record. The initial measurement plan, the Federal Register notice, the public comments received, and the NTIA responses to the comments can be obtained from the NTIA website or directly from NTIA/OSM upon request.

One of the immediate difficulties encountered in establishing a methodology for measuring the impact of UWB emissions to GPS receivers was the lack of documented performance criteria for GPS receivers intended for applications other than aviation. After researching available technical standards and other open literature, a set of criteria that was not application specific was adopted for assessing the performance of the GPS receivers in this measurement effort. The two performance criteria examined were "break-lock" and "reacquisition." Break-lock refers to the loss of signal lock between the GPS receiver and a GPS satellite. This condition occurs when an interfering signal reduces the carrier-to-noise density (C/N_0) ratio (i.e., an increase in the undesired signal level, N_0, relative to the desired signal level, C) to such an extent that the GPS receiver can no longer adequately determine the pseudorange (the initial/uncorrected measure of distance from a single GPS satellite to a receiver) for the given satellite signal. Within this measurement effort, the occurrence of a break-lock condition was as reported by the receiver. Depending on the receiver application, this condition could be a function of cycle slips, or a loss of carrier or phase lock. The reacquisition threshold refers to the UWB power level at which an abrupt increase from the nominal reacquisition time was observed.

To determine the impact on reacquisition time, the signal from the GPS satellite of interest was interrupted and a 50-meter step in pseudorange was introduced over a 10-second period. This was done to simulate a GPS-equipped vehicle passing behind a building or other obstacle in the satellite-to-receiver path, causing a temporary loss-of-lock between the GPS receiver and the satellite of interest. As the vehicle clears the obstacle and the satellite again becomes visible, the GPS receiver must be able to reacquire the lost satellite in the presence of UWB energy in a time consistent with that associated with no UWB energy present. In order to determine the maximum UWB level at which this can be accomplished, the UWB signal was reduced from the

[24] National Telecommunications and Information Administration, Notice, Request for Comments on Global Positioning System/Ultrawideband Measurement Plan, Federal Register, Vol. 65, No. 157 (Aug. 14, 2000), at 49544.

power level at which break-lock occurred until the receiver was able to reacquire the lost satellite in a time correspondent with the nominal receiver reacquisition time with no UWB signal present.

The UWB power level that results in receiver break-lock is not the preferred criterion for determining the interference threshold because it represents an extreme penalty to the performance of a GPS receiver. Thus, the interference threshold adopted for these measurements was the UWB signal level that resulted in a abrupt increase in the reacquisition time.[25] However, for some UWB signal permutations (e.g., those deemed to be CW-like signals), a statistical parameter such as reacquisition time could not be obtained due to limitations associated with the available test equipment (see discussion in Section 2.1.1 of this report). For these cases, break-lock was the only criterion available to perform an analysis of the measured results. Thus, for the subsequent evaluation of the measured data, the break-lock interference threshold was used in those cases where a reacquisition threshold could not be determined. This use of break-lock as the basis for establishing an interference threshold was done solely to facilitate the examination of potential trends in the data and should not be interpreted as an endorsement of the use of break-lock as an interference threshold on which to establish final rules for UWB operation.

The next challenge encountered was how to determine a representative sample of GPS receivers. Since GPS receivers are used in a myriad of applications, including navigation (aviation, space, maritime, rail, and vehicular), position determination (surveying, asset tracking, E-911), and timing (banking, power distribution, Internet synchronization), to name but a few, it is not feasible to attempt to measure a representative receiver from each possible application. Instead, NTIA decided to select candidate GPS receivers based upon the various available GPS receiver architectures. One receiver from each of three basic receiver architectures were identified for inclusion in the measurements: coarse acquisition (C/A)-code tracking receivers, which make up a significant share of the GPS receivers in use today, semi-codeless receivers used in low-dynamic applications requiring high precision (e.g., surveying and reference stations), and C/A-code tracking receivers employing multiple, narrowly-spaced correlators to enhance accuracy and mitigate the effects of multipath. These three GPS receiver architectures encompass most, if not all, of the existing civil GPS applications.[26] In order to address particular concerns related to an aviation use of GPS, a Technical Standard Order (TSO)-C129a compliant aviation receiver (as currently used in en-route and non-precision approach) was also included.[27] The assessment of potential UWB interference to aviation precision approach operations is currently being addressed in a Department of Transportation sponsored study and therefore was not considered in the scope of this effort.

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[25] It should be noted that initial acquisition of a GPS satellite signal is an even more stringent performance criterion for GPS operations. However, this is an extremely difficult criteria to measure and is also highly dependent on manufacturer-specific receiver algorithms. Therefore, it was not considered feasible for use in this effort. A 6 dB factor is often used in GPS interference analyses to account for the greater sensitivity of initial satellite acquisition over the satellite tracking mode of operation.

[26] This effort did not consider the potential impact of UWB operations to military GPS receivers.

[27] Due to unanticipated delays in the execution of the measurement component of this study, the measured data for the narrowly-spaced GPS correlator receiver architecture and the TSO-C129a-compliant receiver were not included in this report. This data will be provided as an addendum to this report as it becomes available.

A third question to be addressed concerned defining the UWB signal(s) to be generated. Since there was little information revealed in the public record with regard to the proposed signal structure of UWB devices intending to operate as an overlay on the GPS band, no single UWB signal structure could be identified that would be representative of a typical UWB transmission system. Therefore, NTIA identified 32 distinct UWB signal structures as being representative of those expected to be used in UWB applications. Those UWB signal permutations identified for examination considered various pulse repetition frequencies (PRFs), modulation schemes, and gating percentages. Each combination of the UWB signal parameters shown in Table 1-1 was used to represent a distinct UWB signal permutation.

The PRF defines the number of pulses transmitted per unit time (one second). The PRF effects the spectral line magnitude and spacing, and the percentage of time that pulses are present.

TABLE 1-1. UWB Permutations Considered in Measurements

UWB Parameter	Parameter Value
PRF	0.1, 1, 5, and 20 MHz (nominal)
Modulation	None, OOK, 2% relative dither, 50% absolute dither
Gating	100% (always on), 20% (4 ms on, 16 ms off)

Gating refers to the process of distributing pulses in bursts by employing a programmed set of periods where the UWB transmitter is turned on or off for a period of pulses. For the measurements performed in this assessment, the gated UWB signal utilized a scheme where a burst of pulses lasting 4 milliseconds (ms) was followed by a 16 ms period when no pulses were transmitted. This is referred to as 20% gating, because the UWB pulses are transmitted 20% of the time. The signal permutations depicted within this report as 100% gating, define a signal where pulses are transmitted 100% of the time.

On-Off Keying (OOK) refers to the process of selectively turning off or eliminating individual pulses to represent data bits.

Dithering refers to the random or pseudo-random spacing of the pulses. Two forms of dithered UWB signals were considered in this effort. These are an absolute referenced dither, where the pulse period is varied in relation to the absolute clock, and a relative referenced dither, where the pulse spacing is varied relative to the previous pulse. The PRF of a relative dithered pulse train is equal to the reciprocal of the mean pulse period. Dithering of the pulses in the time domain spreads the spectral line content of a UWB signal in the frequency domain making the signal appear more noise-like.

The data collected from these measurements are applicable only to the UWB signal permutations that were considered in this assessment. No attempt should be made to extrapolate this data beyond those particular UWB parameters.

A GPS satellite simulator was used to provide simulated GPS signals from a four satellite constellation based on ephemeris data taken from an actual GPS constellation present on December 16, 1999. In the test constellation, one satellite was located at or near the zenith while the remaining three satellites were positioned near the horizon. The GPS receiver channel processing the signal from the near-zenith satellite was monitored for these measurements. This satellite was selected as the satellite to monitor because it has the least Doppler shift during the duration of the measurements. For the measurements performed on the C/A-code receiver, the power of the near-zenith satellite was set to the minimum specification level of -160 dBW.[28] The remaining three satellites were set to a power level 5 dB higher (-155 dBW). The higher power level was used for the remaining satellites so that a break-lock condition would not occur for these signals prior to break-lock of the monitored signal. The value of 5 dB was selected so that UWB power increments of 3 dB could be used to induce break-lock only on the receiver channel being monitored. For the measurements of the semi-codeless GPS receiver, which utilizes the GPS precision (P)-code, the GPS L1 and L2 power levels were set to -163 dBW. Except for the provision of an L2 signal and the power used, all other constellation parameters were consistent. All of the conducted measurements in this effort were performed over a 55-minute evolution of the constellation. The constellation was then reset for the subsequent test condition (e.g., another UWB signal permutation. More detailed information on this test constellation is presented in the ITS Report.[29]

A broadband noise signal was generated using a noise diode to represent the noise contribution from the cross-correlation phenomenon associated with the use of the relatively short Gold Codes in the GPS C/A signal. This cross-correlation noise arises because within a GPS receiver channel, the signals generated from GPS satellites other than the one being monitored by that channel, appear as undesired noise. This phenomenon is well documented in the open literature and the value used in this analysis is based upon work done within the International Telecommunication Union-Radiocommunication Sector (ITU-R).[30] This broadband noise was input to the GPS receiver at a level of -93 dBm/20 MHz (as derived for the minimum C/N_0 of 34 dB-Hz identified in the ITU-R work) in the measurements of all of the GPS receivers examined with the exception of the semi-codeless receiver. Since this receiver utilizes the longer P-code GPS signals on L1 and L2, the cross-correlation noise attributed to the shorter Gold codes used with the C/A signal is not applicable.

For the single source interaction (i.e., a single UWB transmitter-to-GPS receiver) measurements, each UWB signal permutation was generated and combined with the simulated GPS satellite signals, and the broadband noise. The combined signal was injected into the GPS receiver at the antenna input. The UWB power level was increased until either the receiver broke lock with the satellite of interest or until the maximum available output power level from the

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[28] Global Positioning System Standard Positioning Service Signal Specification, 2nd Edition, GPS NAVSTAR, (June 2, 1995) at 18.

[29] ITS Report at 4-3.

[30] Recommendation ITU-R M.1477, Technical and Performance Characteristics of Current and Planned RNSS (Space-to-Earth) and ARNS Receivers to be Considered in Interference Studies in the Band 1559-1610 MHz, at section 3.2, (hereinafter "ITU-R M.1477").

UWB generator was reached. Plots of GPS receiver performance criteria (e.g., break-lock and reacquisition interference levels) were produced for each UWB signal permutation measured. From these plots, the UWB average power level at which the performance criteria was determined and recorded. Data for additional GPS performance parameters (e.g., cycle slips and pseudorange error) were also recorded and are provided in the ITS Report.[31]

An additional set of measurements was performed to provide data that will indicate: 1) how individual UWB signals add to yield an effective aggregate power level, and 2) whether multiple UWB transmitting devices, each of which might be individually tolerated by a GPS receiver, will combine to create an aggregate interference level that will degrade the receiver performance. These aggregate measurements consisted of five measurement cases, each incorporating up to six UWB generators employing various combinations of UWB signal parameters (e.g., PRF, gating, and dithering).

In both the single-source and the aggregate interaction measurements described thus far, all signals were provided to the GPS receiver via a conducted path. Under actual operational conditions, both the UWB transmitting device and the GPS receiver will use antenna subsystems to transmit and receive radio frequency signals. Inherent in the conducted measurements is the assumption that the magnitude and phase distortion of the UWB signal is minimal over the GPS L1 band, for which the associated GPS antenna and preamplifier are designed to operate. Thus, there should essentially be no difference in the UWB signal as seen by the GPS receiver over the frequency range of interest, whether the signal is provided to the receiver through a conducted or radiated path. To verify these assumptions, a measurement was performed to determine that the signals passed through the two paths, conducted and radiated, are consistent. In all of the conducted measurements performed in this effort, the preamplifier recommended for use with the GPS receiver under test was modeled according to manufacturer specifications.

Both the initial measurement plan and the ITS Report contain more detail on these measurement procedures, including information on the measurement equipment used, test set-ups, and calibration procedures. These are available on the NTIA and ITS websites or directly from NTIA upon request.

1.3.2 Analysis Approach

In order to calculate the maximum allowable EIRP, referenced to the output of a UWB transmit antenna, a typical source-path-receiver analysis must be performed. The basic parameters that must be defined for this type of analysis are the receiver interference threshold, the source output power and antenna gain, the propagation path between the transmitter and the receiver, and the antenna gain of the receiver in the direction of the source transmitter. The data obtained from the ITS measurements defines the interference threshold level at the input of the GPS receiver as a function of UWB signal structure (e.g., power, PRF, modulation scheme) for each of the GPS receiver architectures examined. The UWB output power and antenna gain combined define the EIRP, which is the variable to be determined from the analysis. In order to make reasonable assumptions regarding the remaining values needed for the analysis, information regarding how the transmitter and receiver can interact within their operating

[31] ITS Report at Appendix F.

environment is necessary. Collectively, this information defines an operational scenario, which establishes how close the two systems may come to one another under actual operating conditions, and the likely orientation of the antennas. This information is then used to compute the propagation loss and the GPS antenna gain in the direction of the UWB transmitting device. The operational scenario can also be used to determine the applicability of factors such as building attenuation, aggregate allowance, and safety margins.

NTIA hosted a series of public meetings to develop scenarios for GPS and envisioned UWB applications to define the applicable operational scenarios to be considered. The meetings were announced in the Federal Register on August 31, 2000.[32] Participation was encouraged within the UWB and GPS communities and among representatives of the interested Federal Agencies. Multispectral Solutions Inc., the National Oceanic and Atmospheric Administration/National Ocean Service/National Geodetic Survey, Time Domain Corporation, the United States Coast Guard (USCG), the U.S. GPS Industry Council, and NTIA submitted pertinent documents. Specific proposals for operational scenarios to be considered included GPS receivers used in the following applications: terrestrial[33] (e.g., public safety applications such as cellular phone embedded E-911 and emergency response vehicle navigation, geographic information systems, precision machine control, and general operations), maritime navigation (in constricted waterways, harbors, docking, and lock operations); railway operations (positive train control), surveying, and aviation (en-route navigation and non-precision approach). The input received at these meetings was used to develop the operational scenarios that were then used in the analyses documented in this report. These scenarios do not represent all possible applications of GPS, however, they do represent a reasonable bound on the parameters necessary to perform the broadly based analyses. For example, the separation distances represented in these scenarios range from a minimum of 2 meters for the embedded E-911 scenario, to a maximum of approximately 300 meters (1000 feet) for the en-route aviation scenario.

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[32] National Telecommunications and Information Administration, Notice of Public Meeting to Develop Global Positioning System/Ultrawideband Operational Scenarios, Federal Register Vol. 65, No. 170 (Aug. 31, 2000) at 52989 (hereinafter "NTIA Notice").

[33] Within the context of this report, terrestrial refers to land-based operations.

SECTION 2.0
MEASUREMENT RESULTS

2.1 SUMMARY OF MEASUREMENT RESULTS

The information presented in this section summarizes the data collected by ITS in the measurement component of this program, including single-entry results, multiple-entry (aggregate) results, radiated results, amplitude probability distribution (APD) results, and comparisons of the measurement results to existing interference limits. This data was extracted from the measurement plots documented in a report published by ITS[34]. There are two methods for performing radio interference measurements; those where the desired and undesired signals are conducted into the test receiver via a cable connection, and those where the signals are radiated into the test receiver via the propagation medium and antenna assembly. For this effort, conducted measurements were used to evaluate the performance of the GPS receivers.

2.1.1 Single-Entry Conducted Measurements

The data in Tables 2-1 and 2-2 summarize the receiver susceptibility measurements collected by ITS to be used in this assessment. The table entries correspond to the maximum tolerable UWB interference levels associated with the GPS receiver performance criteria adopted for this program. These points were extracted from the data curves presented in the ITS Report. Although each individual data plot is not reproduced within this report, a representative plot is provided in Figure 2-1 to illustrate how the data points associated with the GPS receiver performance criteria were obtained.

The break-lock and reacquisition threshold data points were taken from the ITS plots as illustrated below. In Figure 2-1, the break-lock level is represented by the heavy vertical line. This value was read directly from the scale on the horizontal axis, and has the units of dBm/20 MHz. There are two curves which represent reacquisition data. The lower curve is the mean reacquisition time measured over 10 trials. The upper curve is the maximum reacquisition time measured within these 10 samples. The interference threshold level for the reacquisition performance criterion was determined by locating the point on the lower curve (mean reacquisition time) corresponding to a sharp increase in the reacquisition time. The threshold level was then read directly from the scale on the horizontal axis, and has the units dBm/20 MHz. The power levels are average values for all single-entry UWB measurements except for the 20% gated signal[35] where the level represents the average power for the time when the signal is gated on. In a limited number of cases, the reacquisition threshold level that was determined by

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[34]ITS Report at Appendix D.

[35]100% gating is a continuous uninterrupted PRF, 20% gating is a pulse train that is on for 4 ms in a 20 ms period.

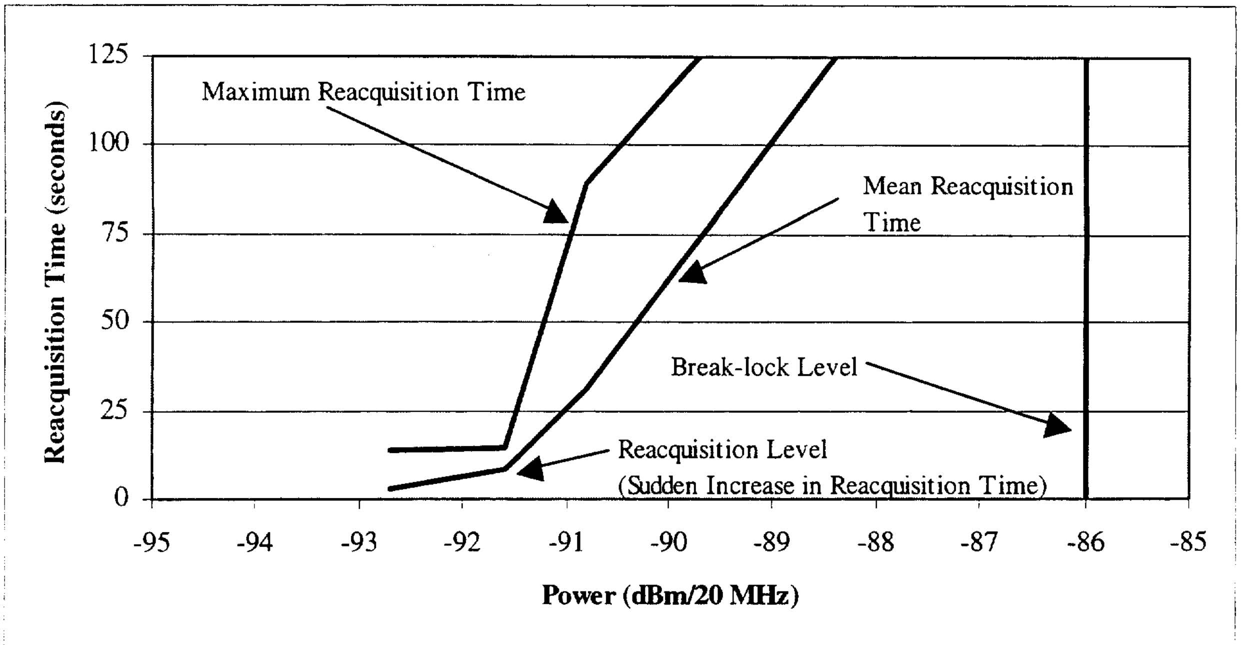

Figure 2-1. Illustration of Power Levels Resulting in Break-lock and Reacquisition

these methods was at a higher interference signal level than the break-lock level. This is attributable to the statistical nature of these measurements where break-lock measurements involve a larger sample size than reacquisition. If a break-lock condition occurs at any time during the longer sampling period, break-lock is declared. In these instances (when the measured break-lock point was at a lower power than reacquisition), the reacquisition level threshold was set equal to the break-lock threshold.

The data used in this assessment, collected by ITS, is represented in Tables 2-1 and 2-2. These tables list the break-lock and reacquisition interference threshold levels for each UWB permutation measured. The tables are organized according to the GPS receiver architectures considered in the analysis.

For those UWB signal permutations that produced spectral lines within the GPS receiver passband, the measurement of a statistical parameter such as reacquisition time, or pseudorange error was not reliable or repeatable given the nature of the moving GPS constellation. To obtain 10 trials of reacquisition time can take as long as 20 minutes. During this time period, the statistics of GPS performance are non-stationary because the Doppler shift of the GPS C/A-Code lines causes them to, at some point, align with the UWB spectral lines. A GPS simulator with the capability of setting the Doppler shift to zero would facilitate collection of the reacquisition data for those UWB signal permutations containing spectral line components. The simulator used in this measurement effort did not have this capability. For this reason, entries in Tables 2-1 and 2-2 which contain an "x" indicate that the performance metric could not be measured with statistical reliability, and therefore is not reported.

TABLE 2-1. Measurement Results for C/A-Code Receiver

Interfering Signal Structure	Interference Susceptibility Levels* (dBm/20 MHz)	
	Break-Lock	Reacquisition
Broadband Noise	-87	-91.5
0.1 MHz PRF, No Mod, 100% Gate	-70	x
0.1 MHz PRF, No Mod, 20% Gate	[-57]	x
0.1 MHz PRF, OOK, 100% Gate	[-60]	x
0.1 MHz PRF, OOK. 20% Gate	[-59.5]	x
0.1 MHz PRF, 50% abs, 100% Gate	[-57]	[-57]
0.1 MHz PRF, 50% abs, 20% Gate	[-56.5]	[-56.5]
0.1 MHz PRF, 2% rel, 100% Gate	[-57]	[-57]
0.1 MHz PRF, 2% rel, 20% Gate	[-57]	[-57]
1 MHz PRF, No Mod, 100% Gate	-100.5	x
1 MHz PRF, No Mod, 20% Gate	[-47.5]	x
1 MHz PRF, OOK, 100% Gate	-78	x
1 MHz PRF, OOK, 20% Gate	[-51]	x
1 MHz PRF, 50% abs, 100% Gate	[-47]	-70
1 MHz PRF, 50% abs, 20% Gate	[-47.5]	[-47.5]
1 MHz PRF, 2% rel, 100% Gate	[-47.5]	-88
1 MHz PRF, 2% rel, 20% Gate	[-47.5]	-47
5 MHz PRF, No Mod, 100% Gate	-108.5	x
5 MHz PRF, No Mod, 20% Gate	-94.5	x
5 MHz PRF, OOK, 100% Gate	-104.5	x
5 MHz PRF, OOK, 20% Gate	-90.5	x
5 MHz PRF, 50% abs, 100% Gate	-86.5	-94
5 MHz PRF, 50% abs, 20% Gate	[-40]	-55
5 MHz PRF, 2% rel, 100% Gate	-85.5	-93.5
5 MHz PRF, 2% rel, 20% Gate	[-39]	[-39]
20 MHz PRF, No Mod, 100% Gate	-115	x
20 MHz PRF, No Mod, 20% Gate	-102	x
20 MHz PRF, OOK, 100% Gate	-111.5	x
20 MHz PRF, OOK, 20% Gate	-99.5	x
20 MHz PRF, 50% abs, 100% Gate	-89.5	-95
20 MHz PRF, 50% abs, 20% Gate	[-34]	-85
20 MHz PRF, 2% rel, 100% Gate	-87	-93
20 MHz PRF, 2% rel, 20% Gate	[-33]	-83

* No measurable effect up to the power level shown in brackets.

TABLE 2-2. Measurement Results for the Semi-Codeless Receiver (Interference only on L1 Frequency)

Interfering Signal Structure	Interference Susceptibility Levels* (dBm/20 MHz)	
	Break-Lock	Reacquisition
Broadband Noise	-102.5	-107
0.1 MHz PRF, No Mod, 100% Gate	[-66]	-75
0.1 MHz PRF, No Mod, 20% Gate	[-66]	[-66]
0.1 MHz PRF, OOK, 100% Gate	[-68]	[-68]
0.1 MHz PRF, OOK. 20% Gate	[-68]	[-68]
0.1 MHz PRF, 50% abs, 100% Gate	-74	-78
0.1 MHz PRF, 50% abs, 20% Gate	[-66]	[-66]
0.1 MHz PRF, 2% rel, 100% Gate	-75	-76
0.1 MHz PRF, 2% rel, 20% Gate	[-66]	-88
1 MHz PRF, 50% abs, 100% Gate	-93.5	-108
1 MHz PRF, 50% abs, 20% Gate	-73	-82
1 MHz PRF, 2% rel, 100% Gate	-99.5	-106
1 MHz PRF, 2% rel, 20% Gate	-81	-84
5 MHz PRF, 50% abs, 100% Gate	-99	-108
5 MHz PRF, 50% abs, 20% Gate	-96.5	-101
5 MHz PRF, 2% rel, 100% Gate	-103	-106
5 MHz PRF, 2% rel, 20% Gate	-92.5	-92.5
20 MHz PRF, No Mod, 100% Gate	-102	x
20 MHz PRF, No Mod, 20% Gate	-98	x
20 MHz PRF, OOK, 100% Gate	-94	x
20 MHz PRF, OOK, 20% Gate	-96	x
20 MHz PRF, 50% abs, 100% Gate	-99.5	-106.5
20 MHz PRF, 50% abs, 20% Gate	-92	-98
20 MHz PRF, 2% rel, 100% Gate	-98.5	-106.5
20 MHz PRF, 2% rel, 20% Gate	-93.5	-93.5

* No measurable effect up to the power level shown in brackets.

Other entries in these tables contain a power level in brackets. This indicates that for some of the UWB signal permutations, the total available power from the UWB simulator was used without resulting in a loss of lock or an impact on reacquisition time for the GPS receiver and the satellite of interest.

2.1.2 Multiple-Entry (Aggregate) Conducted Measurements

As part of this measurement and analysis effort, a limited number of test cases were measured where the interference signal was a composite representing several UWB emitters operating simultaneously. Table 2-3 provides a list of the UWB parameters considered in each aggregate measurement. During these tests, there was no attempt to synchronize the transmissions of the UWB signal generators. NTIA is not aware of any applications that uses synchronized UWB transmissions. For example, through-the-wall imaging radars transmit in bursts and wireless local area networks are packet radios that essentially transmit in bursts. Although the measurement configuration may be used to synchronize the transmissions from multiple UWB sources, NTIA believes that such a configuration is not of practical interest or utility. That is, the UWB system hardware cost and/or data overhead to synchronize emissions would seem to be prohibitive for what is envisioned for a low cost system. Furthermore, for the pulses from several synchronized UWB transmission systems to overlap at the GPS receiver would require the distance to each UWB transmission system to be the same to within less than 1 meter (assuming a 1 nanosecond pulse width). For the aggregate measurements, the unit-under-test was the C/A-code receiver.

TABLE 2-3. UWB Signal Parameters for Aggregate Measurements

Measurement Case	**UWB Signal Parameters** Measure combined interference power at receiver input over a range to obtain break-lock and reacquisition data
I	PRF: *10 MHz (#1); 10 MHz (#2); 10 MHz (#3); 10 MHz (#4); 10 MHz (#5); 10 MHz (#6)* Gating: 100 % Dithering: 2% Rel.
II	PRF: *10 MHz (#1); 10 MHz (#2); 10 MHz (#3); 10 MHz (#4); 10 MHz (#5); 10 MHz (#6)* Gating: 20 % Dithering: 2% Rel.
III	PRF: *10 MHz (#1); 10 MHz (#2); 3 MHz (#3); 3 MHz (#4); 3 MHz (#5); 3 MHz (#6)* Gating: 100 % (#1, #2, #3); 20% (#4, #5, #6) Dithering: No dithering (#1, #2, #3), 2% Rel. (#4, #5, #6)
IV	PRF: *3 MHz (#1); 3 MHz (#2); 3 MHz (#3); 3 MHz (#4); 3 MHz (#5); 3 MHz (#6)* Gating: 20 % Dithering: No dithering (#1, #2, #3, #4), 2% Rel. (#5, #6)
V	PRF: *1 MHz (#1); 1 MHz (#2); 1 MHz (#3); 1 MHz (#4); 1MHz (#5); 1MHz (#6)* Gating: 100 % Dithering: 2% Rel. Perform tests with only UWB signal generator #1on; with #1 and #2 on; with #1, #2 and #3 on and with all four on; etc. until all six generators are on.

In Measurement Cases I through IV, the power level of each UWB signal generator (with the signal parameters of Table 2-3) was set such that they were equal at the input to the UWB signal combiner. The power level associated with each gated signal (to determine equality at the input to the UWB signal combiner) was the average power during the time the UWB signal was gated on. The aggregate UWB power (all signal sources turned on) into the GPS receiver was then controlled by attenuators after the output of the UWB signal combiner. The aggregate UWB power shown on the measured data plots is the total power without gating of any UWB signal. The exact PRF of each UWB signal generator that caused CW-like interference was adjusted to assure that: 1) one spectral line from each generator was within several kHz of the GPS L1 center frequency of 1575.42 MHz, and 2) the spectral lines, from multiple sources, were not coincident in frequency. With the above conditions, the aggregate UWB signal, noise and GPS signals were input to the GPS receiver. The aggregate signal power level was varied and the GPS receiver performance was measured.

In Measurement Case V, the power level of each UWB signal was set such that they were equal at the input of the UWB signal combiner when turned on. However, the first set of GPS receiver performance tests within Measurement Case V was performed with only a single UWB signal generator turned on. The test was repeated with two UWB signal generators turned on. Tests were also performed with three, four, five and then six UWB signal generators turned on.

The break-lock and reacquisition threshold levels were extracted from the ITS plots for aggregate measurements.[36] The methods used to determine these thresholds were the same as those outlined in Section 2-1. The break-lock and reacquisition threshold levels are listed in Table 2-4.

2.1.3 Radiated (Anechoic Chamber) Measurements

To examine the applicability of the conducted measurements, the effects of the GPS antenna on the radiated signals within the frequency band of interest were measured. Measurements were performed wherein the UWB signal was radiated and received within an anechoic chamber. This characterized the effects of the GPS antenna on the UWB signal. These measurements were performed in an anechoic chamber to prevent outside interference sources from affecting the results. The test set-up is shown in Figure 2-2.

A comparison between the radiated and conducted path measurements of the APD and the analyses of the magnitude distortion and the variations in the group delay presented in the ITS Report[37] indicate that the GPS antenna gain in the direction of the interference source is the only parameter that needs to be considered in the source-path-receiver analyses. The GPS antenna does not cause any additional effects to the portion of the UWB signal within the GPS operating band.

[36] ITS Report at Appendix F.

[37] ITS Report at 44.

TABLE 2-4. Results of Aggregate Measurements for C/A-Code Receiver

Measurement Case	Interference Thresholds* (dBm/20 MHz) (combined interference power at receiver input as measured without gating)	
	Break-Lock	Reacquisition
I	-87.5	-94.5
II	-79.5	-86
III	-109	-109
IV	-88	-90
V (One UWB Generator)	[-48]	-88
V (Two UWB Generators)	[-62.5]	-93
V (Three UWB Generators)	-85	-93
V (Four UWB Generators)	-83.5	-93
V (Five UWB Generators)	-84	-94
V (Six UWB Generators)	-83.5	-93

* No measurable effect up to the power level shown in brackets.

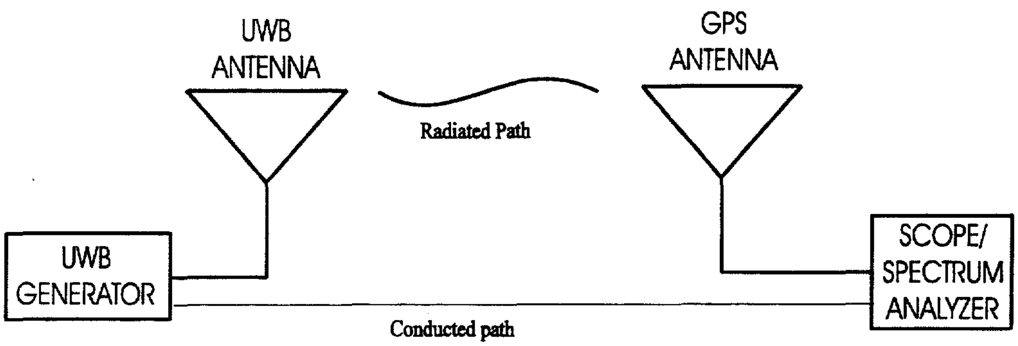

Figure 2-2. Radiated Measurement Test Setup.

2.1.4 Amplitude Probability Distribution Measurements

The APD is used in radio engineering to describe signal amplitude statistics. The APD contains information on the percentage of time the envelope of UWB signals in a specific intermediate frequency (IF) bandwidth exceeds various amplitudes. Statistics such as percentiles, deciles and the median can be read directly from the APD. Other parameters such as average power can also be computed from the APD. The APDs can also be used in determining the interference effect characteristics of UWB signal permutations (e.g., CW-like, noise-like, or pulse-like).

In this effort, APDs were measured in 3 MHz and 20 MHz bandwidths (typical of GPS receiver IF bandwidths), at the GPS L1 center frequency of 1575.42 MHz, for each UWB signal permutation considered. A discussion on APDs, as well as the APDs measured as a part of this program are presented in the ITS Report.[38]

2.2 COMPARISON OF MEASURED RESULTS WITH EXISTING GPS C/A-CODE INTERFERENCE LIMITS

2.2.1 Discussion of Existing GPS Interference Limits

NTIA compared the measured results with existing interference limits applicable to C/A-code GPS receivers. This was done to 1) determine whether the measured interference thresholds were significantly different than existing protection requirements and 2) assess the consistency of the measured data.

The existing interference limits for C/A-code GPS receivers have been developed by a body of GPS experts within the RTCA and the ITU-R. The RTCA limits consider interference signals that are characterized as pulsed, CW, and broadband noise. The ITU-R Recommendation considers CW and broadband noise-like interference signals. For the case of in-band pulsed interference, the RTCA derived limit is a peak power of +20 dBm for pulse widths less than 1 ms and pulse duty cycles less than 10%. For the in-band CW interference case, both the RTCA and the ITU-R interference limits are defined as -150.5 dBW for GPS receivers operating in the tracking mode. For in-band broadband noise interference, both the RTCA and the ITU-R limits are -140.5 dBW/MHz for GPS receivers when operating in the tracking mode.

The RTCA and the ITU-R interference limits are referenced to the input of the GPS receiver and are based on a minimum available GPS C/A-code signal level of -134.5 dBm (-130 dBm minimum guaranteed signal level into a -4.5 dBic antenna),[39] also referenced to the input of the GPS receiver. Since the measurements reported in this effort are based on a GPS signal level of -130 dBm (i.e., GPS antenna gain assumed to be 0 dBic), it was necessary to adjust the interference data by -4.5 dB to account for the difference in desired signal level. The adjustment in this case takes into account that the performance of GPS is dependent on the carrier to noise

[38] ITS Report at Appendix C.

[39] Document Number RTCA/DO-229B, Minimum Operational Performance Standard for GPS/ Wide Area Augmentation System Airborne Equipment (January.1996) at 38 (hereinafter DO-229B); ITU-R M.1477 at ANNEX 1, Section 3-2.

(including receiver thermal noise) ratio. That is, over the range of parameters of interest, with CW-like and noise-like interference, performance is not a function of absolute power levels. Thus, if the desired GPS signal is decreased by 4.5 dB, then the effective interference needs to be decreased by 4.5 dB to maintain the same GPS performance for comparison with existing limits.

2.2.2 Analysis of the Single-Entry Measured Data

The measured UWB interference effect on the GPS receiver for each UWB permutation considered was classified as either pulse-like, CW-like, or noise-like. The pulse-like category is primarily developed as a result of the bandlimiting filter in the GPS receiver. That is, the bandwidth of the UWB signal is typically several orders of magnitude wider than the bandlimiting filters in the GPS receiver. Thus, the pulse shape and bandwidth of the bandlimited pulse corresponds to the impulse response of the receiver filter. Pulses are independent when the filter bandwidth is greater than the pulse repetition rate. That is consecutive independent pulses, at the output of the bandlimiting filter, do not overlap in the time domain. Pulses that were independent without dithering can overlap when dithering is introduced. To remain independent, the minimum pulse repetition period of the dithered signal must be greater than the duration of the filter impulse response. If the bandlimited pulse is independent and of sufficient amplitude, it will saturate one or more elements in the receiver during the pulse period. This will result in "holes" in the GPS signal. If these "holes" are relatively short and of a relatively low duty cycle, they will not seriously degrade the GPS performance. An increase in the amplitude of the pulse will not significantly increase the width of the "holes" and thus the interference effect is somewhat independent of UWB signal strength as long as the amplitude is below the receiver peak pulse power limit (≈+20 dBm). These effects are represented in the RTCA interference limits for pulsed interference.

Typical GPS receivers have an IF bandwidth on the order of several MHz to 20 MHz, therefore, the pulses for most of the 0.1 MHz and 1.0 MHz PRF UWB signal permutations are independent and can be classified as pulse-like. An examination of the data in Table 2-1 reveals only three UWB signal permutations utilizing a 0.1 or 1.0 MHz PRF where a break-lock condition could be measured. These three specific permutations are defined by 0.1 MHz PRF, no modulation, 100% gating; 1 MHz PRF, no modulation, 100% gating; and 1 MHz PRF, OOK, 100% gating. For two of these permutations (0.1 MHz PRF, no modulation, 100% gating and the 1 MHz PRF, OOK, 100% gating), the break-lock interference levels are relatively high (-70 and -78 dBm/20 MHz). An examination of the APDs for these permutations showed signals of a relatively high level for 10% or less of the time. Thus, these two permutations were also considered to represent pulse-like interference conditions as indicated in Table 2-5. The inability to measure a break-lock condition within the available power of the UWB generator, and the PRFs involved, was judged to be indicative of signals that appear pulse-like in the GPS receiver. Four other signal permutations were also judged to be indicative of pulse-like interference signals. These four permutations all employed dithering and gating. For all four of these permutations, break-lock could not be attained with the maximum signal power available from the UWB generator.

The UWB signal permutations that had a pulse-like interference effect are shown in Table 2-5. A direct comparison with the RTCA limit could not be made since break-lock was not attainable within the output signal power limits of the measurement set-up. Furthermore, a continued increase in signal power for these permutations could result in damage to the front-end of the receivers via burn-out, and thus was not pursued as a part of this effort. However, it can be seen from the last data point obtained (i.e., the maximum available signal power) that for a UWB signal that causes pulse-like interference, the GPS receiver performance was fairly robust.

The next category of UWB permutations examined were those that appeared to cause CW-like interference. The decision to categorize a UWB permutation as CW-like was primarily based on whether the UWB signal showed dominant lines in the spectra. This CW-like characteristic was then confirmed by examining the APD for that signal permutation. An additional factor in determining whether a particular UWB permutation demonstrated CW-like characteristics was the fact that a reacquisition measurement could not be reliably performed due to the non-stationary statistics for this GPS performance parameter when CW interference occurred. The obvious case of UWB signals that are CW-like in their impact to GPS receivers are those UWB signal permutations with constant PRFs (i.e., employing no modulation). The spectral lines produced in the emissions of such UWB permutations with PRFs of 1 MHz or greater, appear as CW interference to a C/A-code tracking GPS receiver. If the spectral lines contained in the UWB signal coincide with a dominant spectral line of the GPS C/A-code signal, the GPS receiver performance can be degraded at a low UWB power level. As a result of the Doppler effects introduced by the motion of the GPS satellites, the C/A- code lines will shift in frequency thus increasing the probability of a spectral line contained within the UWB signal coinciding with a dominant C/A-code line. Based on the analytical work performed within the RTCA and the ITU-R, GPS receivers are most susceptible to CW interference. Other UWB signals with non-dithered PRFs of 5 and 20 MHz employing OOK modulation[40], gating (20%)[41], or combinations of OOK modulation and gating will also demonstrate strong CW components. The existence of CW lines for these cases is indicated in the ITS report. The UWB signal permutations considered in this effort that were determined to cause CW-like interference are shown in Table 2-5.

The remaining UWB signal permutations considered in this effort (5 and 20 MHz, 100% gated, with 2% relative or 50% absolute dithering) were determined to cause noise-like interference based on examination of the associated APDs. These are shown as the last of the entries in Table 2-5.

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[40]ITS Report at 59.

[41]ITS Report at 13.

TABLE 2-5. Categorization of UWB Signal Permutations

Interfering Signal Structure	Category Of Interfering Signal Effect	Adjusted Interference Threshold
0.1 MHz PRF, No Mod, 100% Gate	Pulse-Like	Direct Comparison to existing GPS protection levels cannot be made due to the fact that the measurement setup could not attain a power level of +20 dBm. The results do, however, indicate a trend of relative GPS robustness when subjected to low duty cycle pulsed interference consistent with the existing RTCA interference threshold.
0.1 MHz PRF, No Mod, 20% Gate	Pulse-Like	
0.1 MHz PRF, OOK, 100% Gate	Pulse-Like	
0.1 MHz PRF, OOK. 20% Gate	Pulse-Like	
0.1 MHz PRF, 50% abs, 100% Gate	Pulse-Like	
0.1 MHz PRF, 50% abs, 20% Gate	Pulse-Like	
0.1 MHz PRF, 2% rel, 100% Gate	Pulse-Like	
0.1 MHz PRF, 2% rel, 20% Gate	Pulse-Like	
1 MHz PRF, No Mod, 20% Gate	Pulse-Like	
1 MHz PRF, OOK, 100% Gate	Pulse-Like	
1 MHz PRF, OOK, 20% Gate	Pulse-Like	
1 MHz PRF, 50% abs, 100% Gate	Pulse-Like	
1 MHz PRF, 50% abs, 20% Gate	Pulse-Like	
1 MHz PRF, 2% rel, 100% Gate	Pulse-Like	
1 MHz PRF, 2% rel, 20% Gate	Pulse-Like	
5 MHz PRF, 50% abs, 20% Gate	Pulse-Like	
5 MHz PRF, 2% rel, 20% Gate	Pulse-Like	
20 MHz PRF, 50% abs, 20% Gate	Pulse-Like	
20 MHz PRF, 2% rel, 20% Gate	Pulse-Like	
1 MHz PRF, No Mod, 100% Gate	CW-Like	-148.5 dBW
5 MHz PRF, No Mod, 100% Gate	CW-Like	-150.0 dBW
5 MHz PRF, No Mod, 20% Gate	CW-Like	-150.0 dBW
5 MHz PRF, OOK, 100% Gate	CW-Like	-149.0 dBW
5 MHz PRF, OOK, 20% Gate	CW-Like	-149.0 dBW
20 MHz PRF, No Mod, 100% Gate	CW-Like	-149.5 dBW
20 MHz PRF, No Mod, 20% Gate	CW-Like	-150.5 dBW
20 MHz PRF, OOK, 100% Gate	CW-Like	-149.0 dBW
20 MHz PRF, OOK, 20% Gate	CW-Like	-151.0 dBW
5 MHz PRF, 50% abs,100% Gate	Noise-Like	-141.5 dBW/MHz
5 MHz PRF,2% rel, 100% Gate	Noise-Like	-141.0 dBW/MHz
20 MHz PRF, 50% abs, 100% Gate	Noise-Like	-142.5 dBW/MHz
20 MHz PRF, 2% rel, 100% Gate	Noise-Like	-140.5 dBW/MHz

2.2.2.1 Comparison of Single-Entry Measurements to Existing Threshold Limits

For the UWB permutations that cause pulse-like interference effects, a direct comparison to the existing limit of +20 dBm (pulse peak power) could not be made due to the fact that the measurement set-up could not attain a power level of +20 dBm. However, at the maximum power available from the UWB generator, the GPS receiver could not be made to lose lock with the satellite of interest. For the two remaining cases, the power required to cause a break-lock was relatively high. These results indicate a trend of relative GPS robustness when subjected to low duty cycle pulsed interference consistent with the existing RTCA interference threshold.[42]

For the case of CW-like interference, the power contained in the UWB spectral line within the GPS passband must be determined. As a result of the non-stationary characteristic of the statistical measures of GPS receiver performance when the CW interfering signal is aligned (or nearly aligned) in frequency with a dominant C/A-code spectral line, it was not possible to obtain a reliable reacquisition. Thus, for the purposes of comparison to the existing interference criteria, the break-lock interference threshold was used for the CW-like signal cases.

An example of the calculation used to adjust the measured data for UWB signal permutations that cause a CW-like interference effect to the basis represented in the development of the existing interference limits is shown in Tables 2-6 through 2-9. The implicit assumption in these comparisons is that the interference mechanism involves one UWB spectral line interfering with a dominant C/A-code spectral line. Table 2-6 shows the necessary adjustments to the measured thresholds for the CW-like UWB signal permutations utilizing a constant PRF (i.e., no modulation).

The adjustment necessary for comparison between the measured interference threshold and the existing protection limits for a UWB signal that causes a CW-like interference effect utilizing OOK modulation includes a 3 dB factor for the division of power between discrete spectral lines and continuous spectrum.[43] Table 2-7 shows the necessary adjustments to the measured threshold.

The adjustments necessary for a UWB signal permutation (causing a CW-like interference effect) utilizing gating include additional factors to account for 1) the average power over the gating period since the power reported in the measurements is the power during the gate-on period (10log 0.2 = -7 dB for 20% gating), 2) the number of major spectral lines contained in the measurement bandwidth (-10log 5 for a 5 MHz PRF), and 3) an adjustment for the spectral spreading due to gating. When gating is applied to signals with spectral lines, the result is the single line of the non-gated case (major spectral lines) are spread into a number of lines where the spacing between the lines is equal to the reciprocal of the gating period (e.g., 1/20 ms or

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[42] DO-229B at 186.

[43] ITS Report at Appendix B.

TABLE 2-6. Adjustments to Measured Level for a Constant PRF UWB Signal

UWB Signal Permutation	5 MHz PRF, No Mod, 100% Gating
Measured Break-Lock Level	-108.5 dBm/20 MHz
Individual Power Adjustments	
Conversion to dBW	-30 dB
Correction for GPS signal level (i.e., from -130 dBm used in measurements to -134.5 dBm used in threshold development)	-4.5 dB
Power in a single spectral line (-10log 5, where 5 represents the number of lines contained in the 20 MHz measurement bandwidth)	-7 dB
Total Power Adjustment	-41.5 dB
Adjusted Break-Lock Level (-108.5 dBm - 41.5 dB)	-150.0 dBW
Interference Threshold Developed in RTCA and ITU-R	-150.5 dBW

TABLE 2-7. Adjustments to Measured Level for a OOK Modulated UWB Signal

UWB Signal Permutation	20 MHz PRF, OOK, 100% Gating
Measured Break-Lock Level	-111.5 dBm/20 MHz
Individual Power Adjustments	
Division of power between discrete spectral lines and continuous spectrum[44]	-3 dB
Conversion to dBW	-30 dB
Correction for GPS signal level (i.e., from -130 dBm used in measurements to -134.5 dBm used in threshold development)	-4.5 dB
Power in a single spectral line (-10log 1, where 1 represents the number of lines contained in the 20 MHz measurement bandwidth)	0 dB
Total Power Adjustment	-37.5 dB
Adjusted Break-Lock Level (-111.5 dBm - 37.5 dB)	-149.0 dBW
Interference Threshold Developed in RTCA and ITU-R	-150.5 dBW

[44] ITS Report at 59.

spectral lines are convolved with a sinc^2 function[45] obtained from the gating envelope.[46] The 50 Hz for the 20% gating considered in this study) and the null spacing of the sinc^2 function is equal to two times the reciprocal of the gated-on time (e.g., 2/4 ms or 500 Hz in this study). The half-power bandwidth of this function is 250 Hz and will contain a significant majority of the total power of the sinc^2 spectrum. Therefore, for a CW-like UWB signal permutation using 20% gating, the half-power bandwidth (250 Hz) will contain 5 spectral lines at 50 Hz spacing. Thus, the adjustment necessary to account for this distribution of power among the spectral lines is -10log(5) = -7 dB in 250 Hz. The adjustments for a CW-like UWB signal permutation using 20% gating are shown in Table 2-8.

The adjustments necessary for a UWB signal permutation (causing a CW-like interference effect) using an OOK modulation and 20% gating are a combination of the adjustments discussed in the previous two examples (Tables 2-7 and 2-8). These required adjustments for a UWB signal permutation employing OOK modulation and 20% gating are summarized below in Table 2-9.

In order to compare UWB signal permutations (causing a noise-like interference effect) to the existing interference thresholds, the adjustments to the measured data include: 1) conversion of power from dBm to dBW, 2) an adjustment to convert from a 20 MHz measurement bandwidth to a 1 MHz reference bandwidth, and 3) a correction of 4.5 dB to adjust for the difference in GPS signal levels. The measured GPS parameter used as the basis of comparison is the reacquisition level. The adjustments to the measured data for the broadband noise measurement are illustrated in Table 2-10. The same process was used to adjust the noise-like UWB signal permutations for comparison to the existing interference limits.

The results shown in these tables and summarized in the last column of Table 2-5 show consistent agreement with the existing protection limits developed within RTCA and ITU-R of -140.5 dBW/MHz for noise-like interfering signals and -150.5 dBW for CW-like interfering signals. The maximum difference between the levels measured in this effort and the existing protection limits is 2 dB. This indicates that the measured data set is consistent within the range of variations of UWB signal permutations measured. It is noted that for the CW-like UWB signal permutations considered in this effort, this comparison is based on break-lock levels rather than reacquisition levels (due to difficulties discussed previously in this section). However, if it is assumed that the reacquisition level is on the order of 2-3 dB lower than the break-lock level, then the consistency between the measured data and the existing protection limits remains strong.

[45]The sinc function is defined as sinc(argument)= Sin(argument)/argument.

[46] ITS Report at 13.